Coherent Photoproduction of Dileptons on Light Nuclei - a New Means to Learn about Vector Mesons

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Abstract

In the last years much work has been done to learn about the properties of the ρ-meson in nuclear matter. In a calculation of the in-medium spectralfunction of the ρ we find that it is strongly modified by baryonic resonances, especially the $D_{13}(1520)$, through its coupling to resonance-hole states. In order to test the predictions of a model for the in-medium properties of the ρ-meson so far mostly heavy-ion collision have been used. We argue that the coherent photoproduction of ρ-mesons yields additional information about the nature of the medium modification. It can be shown that the production amplitude is sensitive on the momentum dependence of the ρ-selfenergy. This can be used to distinguish experimentally between various models for the ρ in matter.

1 Introduction

The question of how the ρ-meson behaves in hot and dense nuclear matter has attracted much attention over the last years. Based on arguments from chiral symmetry, one expects that the ρ-meson mass changes in the vicinity of the chiral phase transition, though chiral symmetry does not tell if its mass goes up or down [1]. The interest in this question was further stimulated by measurements of dilepton spectra from heavy-ion collions, which were carried out by the NA45 collaboration [2]. These spectra seem to indicate a mass-shift of the ρ-meson down to lower masses of about 100 MeV.

In order to understand this effect various theory groups [3, 4, 5, 6, 7, 8, 9] performed calculations of the selfenergy of the ρ-meson at finite density, which contains all the information about its mass and decay width in nuclear matter. The models differ a lot in what they predict for the in-medium properties of the ρ-meson, the results ranging from a mass-shift of the ρ [3]to a selfenergy, which

clearly shows resonant structures from the excitation of baryonic resonances, especially the $D_{13}(1520)$ [9]. However, if one uses these selfenergies to calculate dilepton spectra in heavy-ion collisions it turns out that they yield very similar results [10] and thus it seems to be very hard to distinguish experimentally between them on the basis of heavy-ion collions.

Therefore it is clearly necessary to find other reactions that yield additional information about the ρ-meson in medium. We claim that the photoproduction of ρ-mesons is a promising candidate for that.

In this talk we will concentrate on a discussion of the coherent photoproduction of ρ-mesons off light nuclei. The term coherent will be explained in section 3. As we will show, this reaction is not only very sensitive to different medium-modifications of the ρ-meson, in addition it also opens up the possibility to study the momentum dependence of the selfenergy of the ρ.

The talk is organized as follows: in section 2 we will briefly review the influence of the excitation of resonance-hole loops on the ρ-selfenergy. In section 3 we will explain the model to calculate the coherent photoproduction before we then turn to the results.

2 The Selfenergy of the ρ-meson in Nuclear Matter

For the study of the mass spectrum of a particle it is convenient to introduce the spectralfunction, which is proportional to the imaginary part of the propagator of the particle. Thus, for a ρ-meson in vacuum, the spectralfunction has the following form:

$$A_\rho^{vac}(q) = \frac{1}{\pi} \frac{\text{Im}\Sigma^{\text{vac}}(q)}{(q^2 - m_\rho^2)^2 + (\text{Im}\Sigma^{\text{vac}}(q))^2} \, ,$$

where

$$\text{Im}\Sigma^{\text{vac}}(q) = \sqrt{q^2} \, \Gamma_{\rho\pi\pi}$$

describes the decay of a ρ-meson into two pions. The spectralfunction gives the probability that the ρ-meson propagates with a mass $m = \sqrt{q^2}$. One sees, that through the coupling to the 2π-channel the ρ-meson can propagate with any mass larger than $2\,m_\pi$ and not only with its rest mass of $m_\rho = 0.768$ MeV.

In nuclear matter there will be additional contributions to the selfenergy from interactions of the ρ with the surrounding nucleons:

$$\Sigma(\omega, \vec{q}) = \Sigma^{vac}(q) + \Sigma^{med}(\omega, \vec{q}) \, .$$

Note that the in-medium part of the selfenergy depends on energy and three-momentum of the ρ-meson independently. This is a direct consequence of the

fact, that there exists a preferred rest frame, namely the rest frame of nuclear matter. Energy and momentum of the ρ-meson are defined with respect to that frame. As a further consequence, transversely and longitudinally polarized ρ-mesons will be modified differently.

At low nuclear densities the ρ-selfenergy can be calculated by means of the *low density theorem*, which relates the selfenergy to the ρN forward-scattering amplitude:

$$\Sigma^{med} = \rho\,\mathcal{T}_{\rho N}(\theta = 0)$$

Thus, at low densities a complete knowledge of the ρN forward-scattering amplitude suffices for a description of the ρ-mass spectrum in nuclear matter. There are various contributions to this amplitude. In this talk we want to concentrate on those scattering processes that lead to the excitation of a baryonic resonance (fig.1):
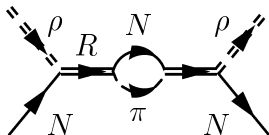

Figure 1: Contribution to the ρN scattering amplitude that leads to the excitation of a baryonic resonance.

The details of the calculation can be found in Peters *et al.* [9], to which the interested reader may refer. In addition, we would like to discuss here some points that have not been mentioned in our previous publication.

If one looks up baryonic resonances which couple to the ρN-channel in [11], one finds some resonances whose mass m_R is below the ρN-threshold:

$$m_R < m_\rho + m_N\,.$$

Among these resonances is for example the $D_{13}(1520)$-resonance which in [9] was found to be very important for the in-medium properties of the ρ-meson. However, keeping in mind that the ρ is an unstable particle, this is not puzzling at all: the resonances simply couple to the low-mass tail of the ρ-spectralfunction.

Direct experimental evidence for that can be found in an analysis from Manley *et al.* [12]. He performed a partial-wave analysis of all existing data for the reaction $\pi N \to \pi\pi N$ within an isobar model, allowing for ρN, $\Delta\pi$ and ϵN as intermediate $\pi\pi N$-states. Here the ϵ represents an isoscalar s-wave $\pi\pi$-state. Because of its importance we want to discuss the case of the
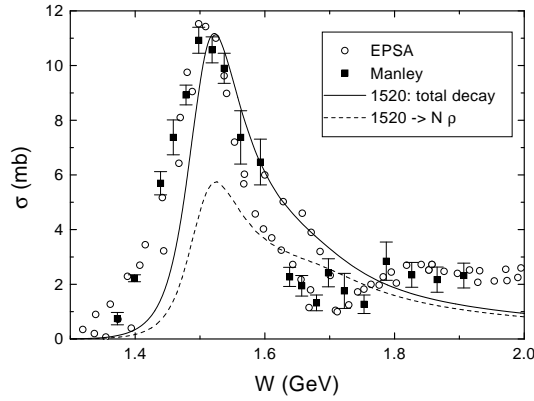
Figure 2: Results for the D_{13}-channel from a partial-wave analysis of $\pi N \to \pi \pi N$-data by Manley [12].

$D_{13}(1520)$-resonance. The result of the analysis for the corresponding partial-wave together with the contribution from the coupling of the resonance to ρN is shown in fig.2 and leaves little doubt that the $D_{13}(1520)$ really decays into ρN.

We mentioned before that the knowledge of the ρN forward-scattering amplitude suffices at low densities for a complete description of the in-medium properties of the ρ-meson. As was pointed out by Friman [13], parts of this amplitude can be compared with the experimental data for the reaction $\pi^- p \to \rho^0 n$. The only available analysis of this is reaction is from Brody $et\ al.$ [14]. It is shown in fig.3 in comparison with a calculation of the cross-section based on our ρN-scattering amplitude.
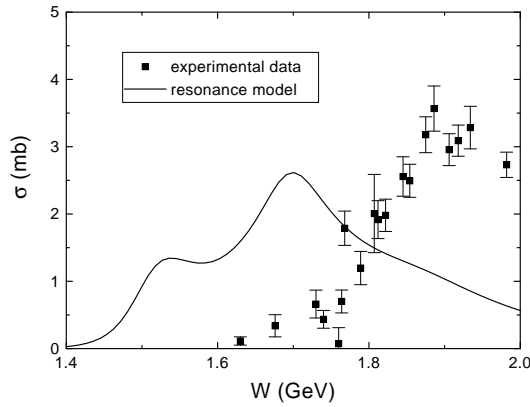

Figure 3: Experimental data for the reaction $\pi^- p \to \rho^0 n$ shown in comparison with a calculation based on the resonance-hole selfenergy. The data are taken from [14]

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The calculation seems to be in clear contradiction to the data. We argue however, that this does not imply that the used model is incorrect, but rather that the extraction of the data at energies $W < 1.7$ GeV is not reliable. The data suggest, for example, that there is no coupling of the $D_{13}(1520)$ to ρN which, as shown above, does not agree with Manleys analysis. The latter was carried out more carefully and is based on a much larger set of data, so we prefer to rely on its results. At higher energies the agreement becomes better, due to the fact that the experimental identification of the ρ-mesons is less problematic.

Before we turn to the coherent photoproduction let us quickly review one main feature of the spectralfunction resulting from the selfenergy discussed above. The calculations show that transverse and longitudinal selfenergy have a very different momentum dependence. At low momenta both exhibit clearly the influence of the $D_{13}(1520)$. However, whereas the spectralfunction for transverse ρ-mesons is nearly flat at high momenta, for longitudinal ρ-mesons the importance of the $D_{13}(1520)$ as well as of the other resonances is reduced and much of the structure coming from the ρ-decay into pions can be found. This will be of great importance in the next section.

3 Coherent Photoproduction of Vector-Mesons

We come now to the discussion of the coherent photoproduction of ρ mesons off light nuclei. By coherent we mean that the ρ is produced elastically, i.e. the nucleus is required to remain in its ground state. Since the ρ-meson has a large decay width, it will decay inside the nucleus. In order to avoid a distortion of the signal due to final state interactions of the decay products, we consider dileptons as the final state. One also has to calculate the dilepton production rate coming from intermediate photon and ω-meson states, wich can not be distinguished experimentally from dileptons from coming ρ-decay.

In impulse approximation the amplitude for the complete process can be put in the form:

$$\mathcal{M} \sim \sum_V \int dm \sum_\alpha \frac{\langle e^+ e^- | \mathcal{O} | V(m) \rangle \langle \alpha\, V(m) | \mathcal{V} | \alpha\, \gamma \rangle}{m^2 - m_V^2 + I\, m\, \Gamma + \Sigma^{med}}$$

Here V represents the produced spin-1 state, m_V its mass, Γ its vacuum decay width and Σ^{med} its selfenergy in nuclear matter. Different scenarios for the medium-modifications of the ρ enter through Σ^{med}. m is the invariant mass of the dileptons. $|\alpha\rangle$ is a bound nucleon state with the quantum numbers α and the sum is over all filled nucleon states in the nucleus under consideration. The potential for the production of a vector-meson is denoted by $\mathcal{V}$ and $\mathcal{O}$ describes the coupling of a vector particle to dilepton.

3.1 The Potential $\mathcal{V}$

The potential $\mathcal{V}$ is taken from Friman *et al.* [15] and describes the photoproduction of vector-mesons within a meson-exchange model. The parameters of the model are adjusted to data for the photoproduction on free nucleons. It turns out that for a reasonable description of the ρ-meson production one needs to take into account the contribution from both π- and σ-exchange, whereas in the case of ω-mesons π-exchange alone suffices. Since the pion is a pseudoscalar particle, π-exchange induces a change of the parity of the nucleus and does therefore not contribute to the amplitude for the coherent production. Thus within our model this amplitude vanishes for ω-mesons.

3.2 The Selfenergy Σ^{med}

The selfenergy Σ^{med} describes how the ρ-meson is modified during its propagation through the nucleus. In our calculation we studied the effects of a selfenergy based on the excitation of resonance-hole loops, which was discussed in the first part of this talk, on the production amplitude. We would like to mention again the main properties of this model, namely that it has a large imaginary part and that it shows a different momentum-dependence of transverse and longitudinal selfenergy.

In order to demonstrate the sensitivity of the amplitude to different models for the in-medium modification of the ρ-meson we also calculated the ρ-selfenergy that follows from the same Lagrangian as the potential $\mathcal{V}$ [15] and which is depicted diagramatically by a tadpole-graph (fig.4).
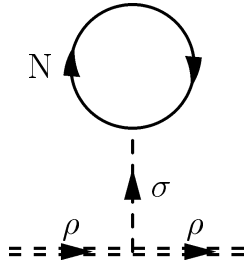

Figure 4: Tadpole contribution to the ρ-selfenergy that follows from the potential $\mathcal{V}$.

In contrast to the resonance-hole model this selfenergy is purely real and leads to a decrease of the ρ-mass of about 100 MeV. Also, it induces the same medium-modification to both transverse and longitudinal ρ-mesons.

3.3 Results

The calculation shows that with our choice of the potential $\mathcal{V}$ the production amplitude is proportional to the nuclear formfactor $F(q)$, where q denotes the momentum transfer. In fig.5 we show the formfactor of ^{12}C. We also indicate the minimal momentum transfer q_{min} for the production of a particle of mass 0.5 GeV and 0.768 GeV at an incident photon energy of 0.85 GeV.
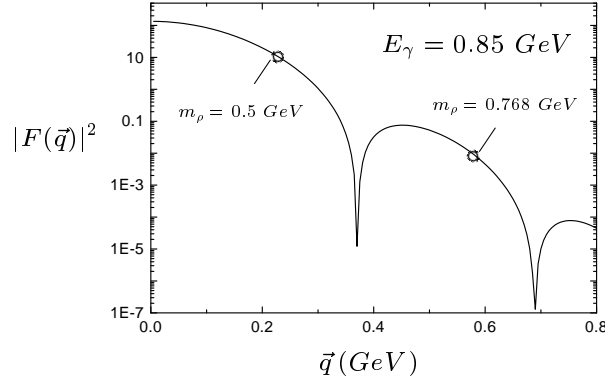

Figure 5: The nuclear formfactor of ^{12}C. Also indicated are the values of q_{min} for the production of a particle of mass 0.5 GeV and 0.768 GeV.

A simple kinematical consideration shows that with dropping mass or increasing photon energy q_{min} becomes smaller.

In general

$$\sigma_{tot} \, , \; \frac{d\sigma}{dm} \propto \int_{q_{min}}^{q_{max}} q|F(q)|^2 \, .$$

Since the formfactor decreases rapidly as q increases, it is clear that the magnitude of the cross-section is mainly determined by the kinematical region around q_{min}. As a direct consequence of the kinematics the nuclear formfactor will therefore strongly favour the production of ρ-mesons lighter than $m_\rho = 0.768$ GeV, whereas the spectralfunction favours ρ-mesons with a mass around m_ρ. Thus one expects that the shape of $\frac{d\sigma}{dm}$ is governed by an interplay between spectralfunction and formfactor and that two peaks will show up in the spectrum.

For the same reason the coherent photoproduction is very sensitive to medium modifications of the ρ-meson. The cross-section for a ρ-meson whose mass is reduced in the nuclear medium will be substantially larger than in the vacuum-case. If on the other side the major effect of the medium is a broadening of the ρ, the cross-section should be reduced due to absorptive effects.

In fig.6 $\frac{d\sigma}{dm}$ for the production of dileptons via vector-mesons is shown for different medium-scenarios at a photon energy of 0.85 GeV. The left plot con-
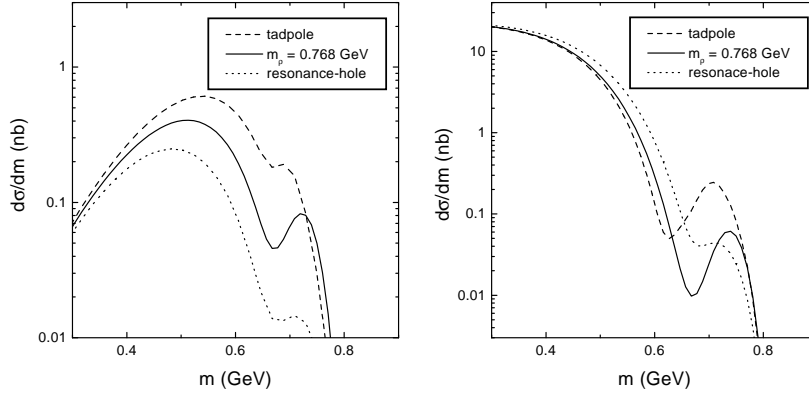
Figure 6: $\frac{d\sigma}{dm}$ of the reaction $\gamma\,{}^{12}C \to V\,{}^{12}C \to e^+e^-\,{}^{12}C$ for various medium-modifications of the ρ-meson. The plot on the left shows the contribution from the ρ alone while on the right one sees the contribution from both ρ and photon.

tains only the contribution from the ρ-meson to the dilepton-spectrum. The results are in line with the previous discussion. Two peaks can be found in the spectrum at $m \sim 0.77$ GeV and at $m \sim 0.55$ GeV. Furthermore, a lower ρ-mass stronlgy enhances the cross-section whereas the resonance-hole model, which predicts a strong broadening of the ρ, gives smaller results. The plot on the right shows $\frac{d\sigma}{dm}$ with the photon included as well. The spectralfunction of the photon enhances the contribution at low masses. Besides, the decay width of a virtual photon into dileptons has a different mass dependence than that of a ρ-meson ($\Gamma_\gamma \sim \frac{1}{m^3}$, but $\Gamma_\rho \sim m$). Both effects lead to a strong enhancement of the cross-section at low masses. However, various medium-modifications of the ρ-meson still lead to quite different results for masses above 0.6 GeV.

The results shown so far did not take into account the polarization of the vector-particles. In view of the very different momentum dependence of the selfenergy for transverse and longitudinal ρ-mesons in the resonance-hole model it is tempting to look at both polarizations separately and thus to turn the momentum dependence directly into an observable. We find that the ratio $R = \frac{d\sigma_{tr}}{dm}/\frac{d\sigma_{long}}{dm}$ is of particular interest. In fig.7 we show R for the two selfenergies discussed above and for the vacuum case. The resonance-hole model leads to a strong enhancement of R in the mass region around 0.6 GeV in comparison to the vacuum case. Since the tadpole-selfenergy is identical for transverse and longitudinal polarizations and since R is proportional to the ratio of both selfenergies, a simple mass-shift scenario gives exactly the same results as one would get for a ρ-meson without any medium modification.
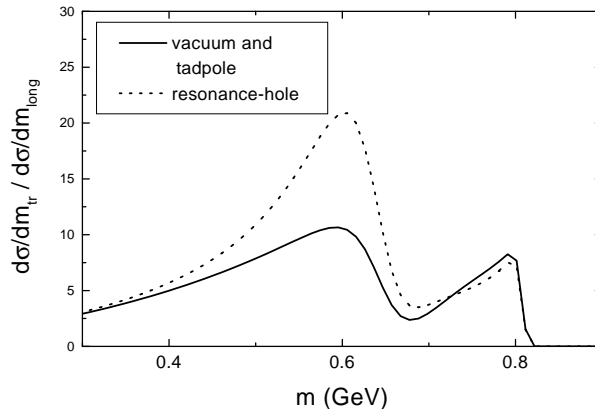
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Figure 7: The ratio R as defined in the text plotted for different medium-modifications of the ρ-meson.

Summary & Outlook

In a calculation of the ρ-selfenergy in nuclear matter we found that the excitation of the $D_{13}(1520)$-resonance in ρN scattering is of great importance for the in-medium properties of the ρ-meson. As a possibility to obtain more information about the ρ in nuclear matter we propose the coherent photoproduction of vector mesons. It was demonstrated that the production rates are quite sensitive to different in-medium scenarios for the ρ-meson. Furthermore, by looking at the polarization of the vector-meson one can obtain valuable information about the momentum dependence of the selfenergy of the ρ.

Further work on this subject will include the calculation of a background contribution, the Bethe-Heitler process [16], to the dilepton spectrum, a more refined version of the potential $\mathcal{V}$, which is consistent with the selfenergy used and a calculation of the ρ-selfenergy in the nucleus rather than in nuclear matter.

Acknowledgements

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